

# Interstellar Extinction Law in the $J$ , $H$ , and $K_S$ Bands toward the Galactic Center

Shogo Nishiyama<sup>1,★</sup>, Tetsuya Nagata<sup>2</sup>, Nobuhiko Kusakabe<sup>3</sup>, Noriyuki Matsunaga<sup>4</sup>,  
Takahiro Naoi<sup>5</sup>, Daisuke Kato<sup>1</sup>, Chie Nagashima<sup>1</sup>, Koji Sugitani<sup>6</sup>, Motohide Tamura<sup>7</sup>,  
Toshihiko Tanabé<sup>4</sup>, and Shuji Sato<sup>1</sup>

## ABSTRACT

We have determined the ratios of total to selective extinction in the near-infrared bands ( $J$ ,  $H$ ,  $K_S$ ) toward the Galactic center from the observations of the region  $|l| \lesssim 2^\circ$  and  $0^\circ 5 \lesssim |b| \lesssim 1^\circ$  with the IRSF telescope and the SIRIUS camera. Using the positions of red clump stars in color-magnitude diagrams as a tracer of the extinction and reddening, we determine the average of the ratios of total to selective extinction to be  $A_{K_S}/E_{H-K_S} = 1.44 \pm 0.01$ ,  $A_{K_S}/E_{J-K_S} = 0.494 \pm 0.006$ , and  $A_H/E_{J-H} = 1.42 \pm 0.02$ , which are significantly smaller than those obtained in previous studies. From these ratios, we estimate that  $A_J : A_H : A_{K_S} = 1 : 0.573 \pm 0.009 : 0.331 \pm 0.004$  and  $E_{J-H}/E_{H-K_S} = 1.72 \pm 0.04$ , and we find that the power law  $A_\lambda \propto \lambda^{-1.99 \pm 0.02}$  is a good approximation over these wavelengths. Moreover, we find a small variation in  $A_{K_S}/E_{H-K_S}$  across our survey. This suggests that the infrared extinction law changes from one line of sight to another, and the so-called “universality” does not necessarily hold in the infrared wavelengths.

*Subject headings:* dust, extinction — stars: horizontal-branch — Galaxy: center

---

<sup>1</sup>Department of Astrophysics, Nagoya University, Nagoya, 464-8602, Japan

★shogo@z.phys.nagoya-u.ac.jp

<sup>2</sup>Department of Astronomy, Kyoto University, Kyoto, 606-8502, Japan

<sup>3</sup>Department of Astronomical Sciences, Graduate University for Advanced Studies (Sokendai), Mitaka, Tokyo, 181-8588, Japan

<sup>4</sup>Institute of Astronomy, School of Science, The University of Tokyo, Mitaka, Tokyo, 181-0015, Japan

<sup>5</sup> Department of Infrared Astrophysics, Institute of Space and Astronautical Science, Japan Aerospace eXploration Agency, Sagami-hara, Kanagawa, 229-8510, Japan

<sup>6</sup>Graduate School of Natural Sciences, Nagoya City University, Nagoya, 464-8602, Japan

<sup>7</sup>National Astronomical Observatory of Japan, Mitaka, Tokyo, 181-8588, Japan

## 1. Introduction

The wavelength dependence of interstellar extinction is not only important information for understanding the nature of interstellar dust grains but an essential ingredient in recovering the intrinsic properties of reddened objects. Change in the interstellar extinction law affects many published conclusions based on the observations of heavily reddened objects, such as photometric distances, the selection of young stellar objects in color-color diagrams, and the age determination of clusters from comparison with isochrones. Since the Galactic center (GC) region is not observable at visible wavelengths due to large interstellar extinction, observations and a precise extinction law at infrared wavelengths are required for the study of objects in the GC. However, accurate determination of the absolute extinction  $A_\lambda$  is not easy in the infrared.

The most widely used technique to obtain the interstellar extinction law is the color-difference (CD) method, in which the extinction curves are determined in the form of the ratios of color excesses  $E_{\lambda-\lambda_1}/E_{\lambda_2-\lambda_1}$  as a function of  $\lambda^{-1}$ . Here  $E_{B-V}$  ( $\lambda_1 = V$  and  $\lambda_2 = B$ ) is customarily used as a standard normalization. The absolute extinction  $A_\lambda$  can be derived from the ratios of color excesses, only if the ratio of total to selective extinction  $R_V = A_V/E_{B-V}$  is evaluated. While the ratio of color excesses is easily observed and thus determined precisely,  $R_V$  cannot be evaluated directly from observed data;  $R_V$  can only be deduced by the *extrapolation* of the extinction curve to  $\lambda^{-1} = 0$  with reference to some model (e.g., van de Hulst 1946) for its behavior at wavelengths beyond the range. The intercept of the extinction curve in the  $E_{\lambda-V}/E_{B-V}$  versus  $\lambda^{-1}$  diagram is  $-R_V$  because

$$\lim_{\lambda^{-1} \rightarrow 0} \frac{E_{\lambda-V}}{E_{B-V}} = \frac{-A_V}{E_{B-V}} = -R_V. \quad (1)$$

In this diagram, then, the total extinction (normalized by  $E_{B-V}$ ) at each wavelength  $\lambda$  is obtained as the vertical distance  $A_\lambda/E_{B-V}$  of each data point from the level of  $-R_V$  through the relation

$$\frac{A_\lambda}{E_{B-V}} = \frac{E_{\lambda-V}}{E_{B-V}} - (-R_V). \quad (2)$$

Unfortunately, the extrapolation has uncertainty due to (1) the contamination by dust emission and (2) the possible existence of neutral extinction by grains much larger than the wavelength of observation. The total extinction value  $A_\lambda$  is derived as the *difference* between the two terms on the right-hand side<sup>1</sup> of eq. [2]. Since the value of eq. [2] is small in

---

<sup>1</sup>Note that  $E_{\lambda-V}$  is negative for the wavelengths  $\lambda$  longer than  $V$ .

the infrared, even a small change in  $R_V$  can have significant influence on the value. Therefore, the accurate determination of  $A_\lambda$  is difficult in the infrared.

Red clump (RC) stars in the Galactic bulge have recently been used to study the extinction law (Woźniak & Stanek 1996), resulting in a precise determination of the ratio of total to selective extinction  $R_\lambda$  (Udalski 2003; Sumi 2004). RC stars are the equivalent of the horizontal-branch stars for a metal-rich population, and they have narrow distributions in luminosity and color with weak dependence on metallicity. In addition, distances to RC stars in the Galactic bulge can be regarded as the same. They thus occupy a distinct region in the color-magnitude diagram (CMD), and can be used as standard candles at an equal distance; they are located in a straight line with a slope of  $R_\lambda = A_\lambda/E_{\lambda'-\lambda}$ , in accordance with the variable extinction to each of them. We refer to this as the “RC method”. The RC method is based on the “variable extinction method” (Krełowski & Papaj 1993) or the “cluster method” (Mihalas & Binney 1981).

In the cluster method, we expect the difference between the observed and absolute magnitudes to be the same for every cluster star except for differences produced by variations in the amount of interstellar extinction along the line of sight to each star (Mihalas & Binney 1981). Therefore, photometry and the determination of the spectral type of each star is necessary to derive the slope  $R_\lambda = A_\lambda/E_{\lambda'-\lambda}$ . Here the amount of interstellar extinction is different, but the interstellar extinction law, and furthermore the property of interstellar dust, is assumed to be identical between the lines of sight. In the real world, we should note that the extinction  $A_\lambda$  might be nothing but an average of possibly variant extinction due to variant dust grains integrated over the whole line of sight.

In the RC method, while this assumption is similarly applied, we select RC star candidates from the CMD and do not have to perform spectroscopy. We can obtain  $R_\lambda$  directly from the observed data, and therefore  $R_\lambda$  can be much more reliable than that obtained by the extrapolation of the extinction curve in the CD method. The reliable  $R_\lambda$  provides the absolute extinction  $A_\lambda$  which is exactly what we want to know. While visible observations of RC stars are restricted to a few windows of low extinction, we can observe highly reddened RC stars at fields very close to the GC in the infrared. Thus, we can use the RC stars near the GC to determine the infrared extinction law very accurately and compare the results with the past determinations for the GC and other lines of sight.

In this paper, we have determined the ratios of total to selective extinction  $A_{K_S}/E_{H-K_S}$ ,  $A_{K_S}/E_{J-K_S}$ , and  $A_H/E_{J-H}$ , and the ratio of absolute extinction  $A_J : A_H : A_{K_S}$ , by adopting the RC method to investigate the extinction law toward the Galactic center.

## 2. Observations

Our observations were obtained in 2002 March–July, and 2003 April–August using the near-infrared camera SIRIUS (Simultaneous Infrared Imager for Unbiased Survey; Nagashima et al. 1999; Nagayama et al. 2003) on the IRSF (Infrared Survey Facility) telescope. IRSF is a 1.4m telescope constructed and operated by Nagoya University and SAAO (South African Astronomical Observatory) at Sutherland, South Africa. The SIRIUS camera can provide  $J(1.25\mu\text{m})$ ,  $H(1.63\mu\text{m})$ , and  $K_S(2.14\mu\text{m})$  images simultaneously, with a field of view of  $7'.7 \times 7'.7$  and a pixel scale of  $0''.45$ .

Over the period 2002-2003, about  $800 \times 3$  ( $J, H, K_S$ ) images were obtained over  $|l| \lesssim 2^\circ$  and  $|b| \lesssim 1^\circ$  (see Fig1). Our observations were obtained only on photometric nights, and the typical seeing was  $1''.2$  FWHM in the  $J$  band. A single image comprises 10 dithered 5 s exposures.

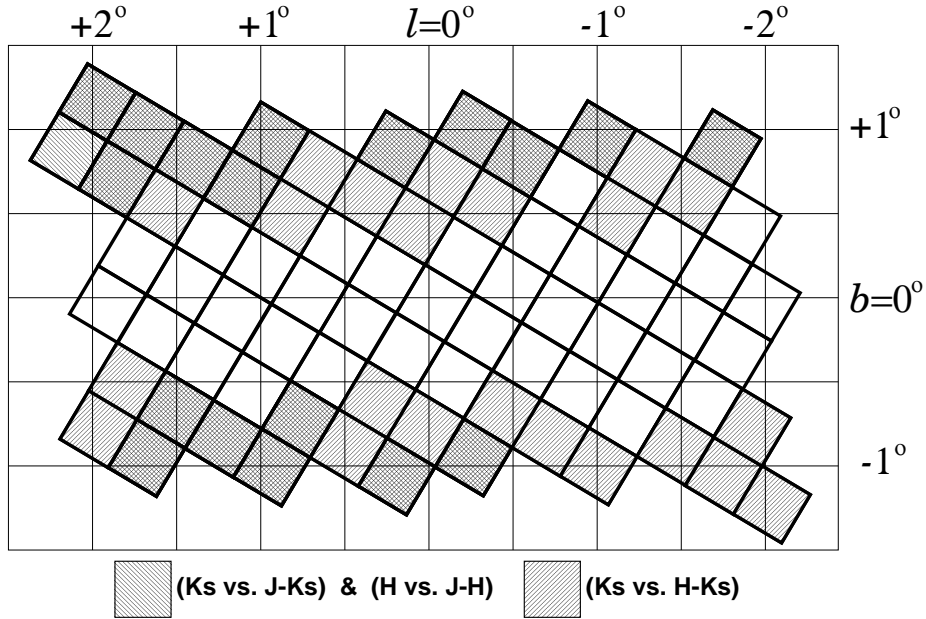


Fig. 1.— Observed area and fields used for data analysis. Each square consists of nine SIRIUS fields. Only the hatched regions were used for the data analysis in this paper. The white squares are the regions where the magnitude and color of RC stars were not reliably determined due to large extinction.

### 3. Reduction and Analysis

Data reduction was carried out with the IRAF (Imaging Reduction and Analysis Facility)<sup>2</sup> software package. Images were pre-reduced following the standard procedures of near-infrared arrays (dark frame subtraction, flat-fielding, and sky subtraction). Photometry, including point-spread function (PSF) fitting, was carried out with the DAOPHOT package (Stetson 1987). We used the `daofind` task to identify point sources, and the sources were then input for PSF-fitting photometry to the `allstar` task. About 20 sources were used to construct the PSF for each image.

Each image was calibrated with the standard star #9172 (Persson et al. 1998), which was observed every hour in 2002 and every half-hour in 2003. We assumed that #9172 has  $J = 12.48$ ,  $H = 12.12$ , and  $K_S = 12.03$  in the IRSF/SIRIUS system. The average of the zero-point uncertainties was about 0.03 mag in the three bands. The averages of the  $10\sigma$  limiting magnitudes were  $J = 17.1$ ,  $H = 16.6$ , and  $K_S = 15.6$ .

To measure the ratios of total to selective extinction  $A_{K_S}/E_{H-K_S}$ ,  $A_{K_S}/E_{J-K_S}$ , and  $A_H/E_{J-H}$ , we selected the bulge RC stars, which constitute a compact and well-defined clump in a CMD. Their mean magnitude and color are thus good references, and we apply the method developed in the  $V$  and  $I$  bands by Udalski (2003) and Sumi (2004).

As a first step we divide each field into four sub-fields of  $\sim 4' \times 4'$  on the sky. Then we construct  $K_S$  versus  $H - K_S$ ,  $K_S$  versus  $J - K_S$ , and  $H$  versus  $J - H$  CMDs. Second, we extract stars in the region of CMDs dominated by RC stars (the rectangular region of the CMD in Fig. 2), and the extracted stars are used to make magnitude (luminosity function: Fig. 2, *upper right*) and color (Fig. 2, *lower left*) histograms. These histograms have clear peaks that can be fitted with a Gaussian function (thick curves in Fig. 2 histograms).

Due to highly nonuniform interstellar extinction over the area surveyed, the RC peaks in CMDs shift from one sight line to another. The peaks shift in the range  $13.4 \lesssim K_S \lesssim 14.6$  and  $0.4 \lesssim H - K_S \lesssim 1.2$ , and therefore we have to shift the region to extract RC stars from sub-field to sub-field. Since the mean  $J$ ,  $H$ , and  $K_S$  magnitudes of RC stars become too faint in highly reddened fields, estimates of the peak magnitudes and the colors of RC stars can be unreliable in such fields. To avoid this problem, we use only the sub-fields in which the peak magnitude of RC stars is more than 1 mag brighter than the  $10\sigma$  limiting magnitudes (Fig.1, *hatched squares*). In addition, we confirmed the completeness to be 85%

---

<sup>2</sup>IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

at  $K_S = 15$  by adding artificial stars into the most crowded image.

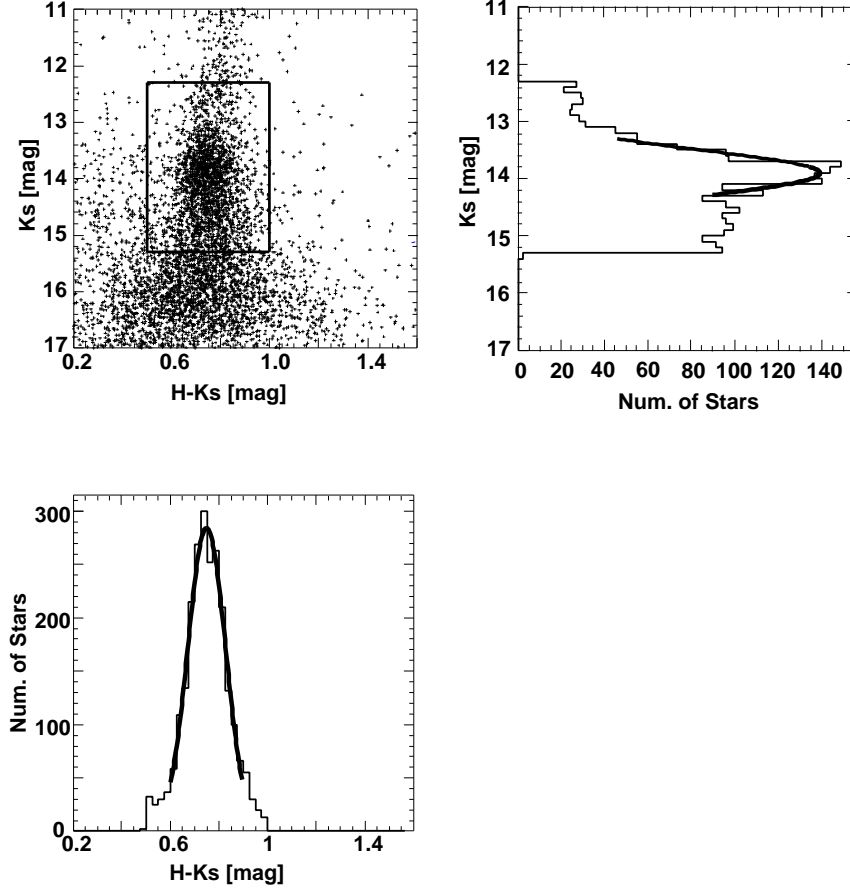


Fig. 2.— *Upper left*: Sample CMD centered at 17h 46m 10.0s, -27d 13m 48.1s. Stars in the rectangle on the CMD are used to estimate the RC peak of color and magnitude. *Upper right*: Luminosity function of selected region in CMD. *Lower*:  $H - K_S$  color histogram of selected region in CMD. Mean color and magnitude are obtained by fitting with Gaussian function.

#### 4. Results

Fig. 3 shows the location of the RC magnitude and color peaks in the  $K_S$  versus  $H - K_S$  (*upper left*),  $K_S$  versus  $J - K_S$  (*upper right*), and  $H$  versus  $J - H$  (*lower*) CMDs. Error bars include uncertainties in the RC peak and the photometric calibration. Solid lines are least-squares fits to the data. If the variations of the RC magnitudes and colors are due to the interstellar extinction, the ratios  $A_{K_S}/E_{H-K_S}$ ,  $A_{K_S}/E_{J-K_S}$ , and  $A_H/E_{J-H}$  can be directly determined by the slopes of the fitting lines. Thus, we obtain  $A_{K_S}/E_{H-K_S} = 1.44 \pm 0.01$ ,  $A_{K_S}/E_{J-K_S} = 0.494 \pm 0.006$ , and  $A_H/E_{J-H} = 1.42 \pm 0.02$ .

$A_{K_S}/E_{H-K_S}$ ,  $A_{K_S}/E_{J-K_S}$ , and  $A_H/E_{J-H}$  provide us with the ratios of absolute extinction,  $A_{K_S}/A_H$ ,  $A_{K_S}/A_J$ , and  $A_H/A_J$ , by which we obtain  $A_J : A_H : A_{K_S} = 1 : 0.573 \pm 0.009 : 0.331 \pm 0.004$ . Here  $A_H/A_J = 0.573$  is the weighted mean of that derived by  $A_H/E_{J-H}$  and that derived by  $A_{K_S}/E_{H-K_S}$  and  $A_{K_S}/E_{J-K_S}$  [i.e., from  $(A_{K_S}/A_J)/(A_{K_S}/A_H)$ ]. Using the ratios  $A_H/E_{J-H} = 1.42 \pm 0.02$  and  $A_H/E_{H-K_S} = 2.43 \pm 0.01$ , in turn, we can determine the most frequently quoted “near-infrared extinction law”, the ratio  $E_{J-H}/E_{H-K_S}$  to be  $1.71 \pm 0.02$ . When we plot the observed peaks of RC stars in the  $J - H$  versus  $H - K_S$  color-color diagram, the slope of peak distribution  $E_{J-H}/E_{H-K_S} = 1.72 \pm 0.04$  (Fig 4) is consistent with this ratio.

To examine the variation of the extinction law we divide the survey region into four sub-regions, N+ ( $+2^\circ > l > 0^\circ, +1^\circ > b > 0^\circ$ ), S+ ( $+2^\circ > l > 0^\circ, 0^\circ > b > -1^\circ$ ), N- ( $0^\circ > l > -2^\circ, +1^\circ > b > 0^\circ$ ), and S- ( $0^\circ > l > -2^\circ, 0^\circ > b > -1^\circ$ ). The CMDs of the divided regions are shown in Fig. 5. The  $A_{K_S}/E_{H-K_S}$  ratios for N+, S+, N-, and S- are  $1.46 \pm 0.02$ ,  $1.45 \pm 0.02$ ,  $1.34 \pm 0.02$ , and  $1.51 \pm 0.03$ , respectively. We can see a small but clear difference from one line of sight to another. As discussed in §5.3, the extinction curve can be approximated by a power-law  $A_\lambda \propto \lambda^{-\alpha}$ . Then the power-law exponents  $\alpha$  for N+, S+, N-, and S- are 1.96, 1.97, 2.09, and 1.91, respectively. The low numbers of data points in CMDs of  $K_S$  versus  $J - K_S$  and  $H$  versus  $J - H$  create uncertainties that are too large to detect variations of similar size to those found in  $A_{K_S}/E_{H-K_S}$ .

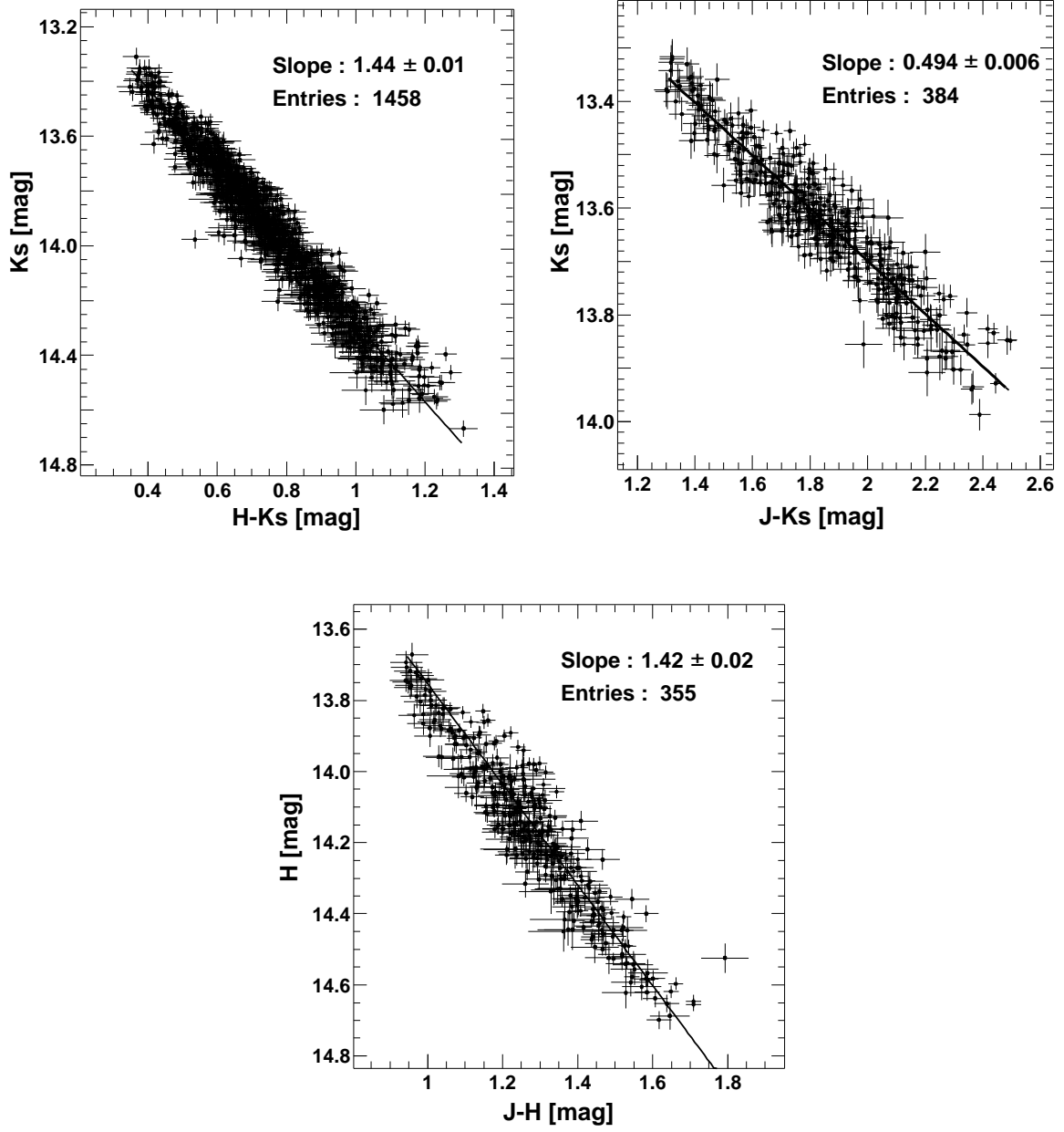


Fig. 3.— Location of RC peaks in  $K_S$  vs.  $H - K_S$  (*upper left*),  $K_S$  vs.  $J - K_S$  (*upper right*), and  $H$  vs.  $J - H$  (*lower*) CMDs. The solid lines are the least-squares fits to the data.



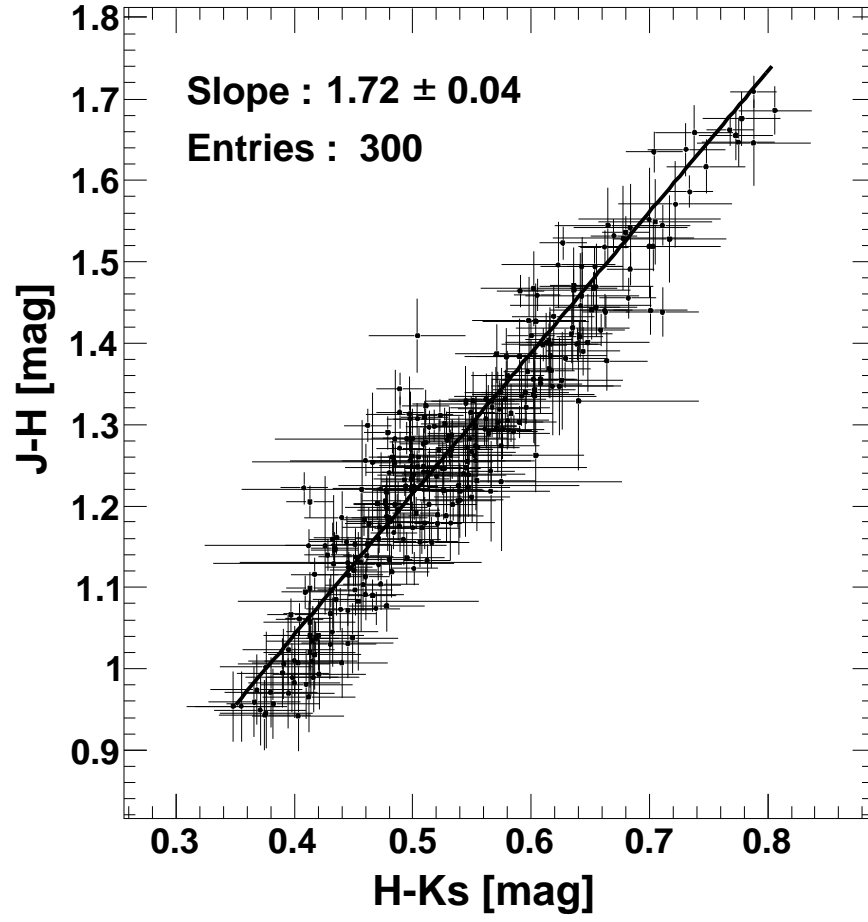


Fig. 4.— Location of the RC peaks in the color-color diagram (  $J - H$  vs.  $H - K_S$  ). The solid line is the least-squares fit to the data.

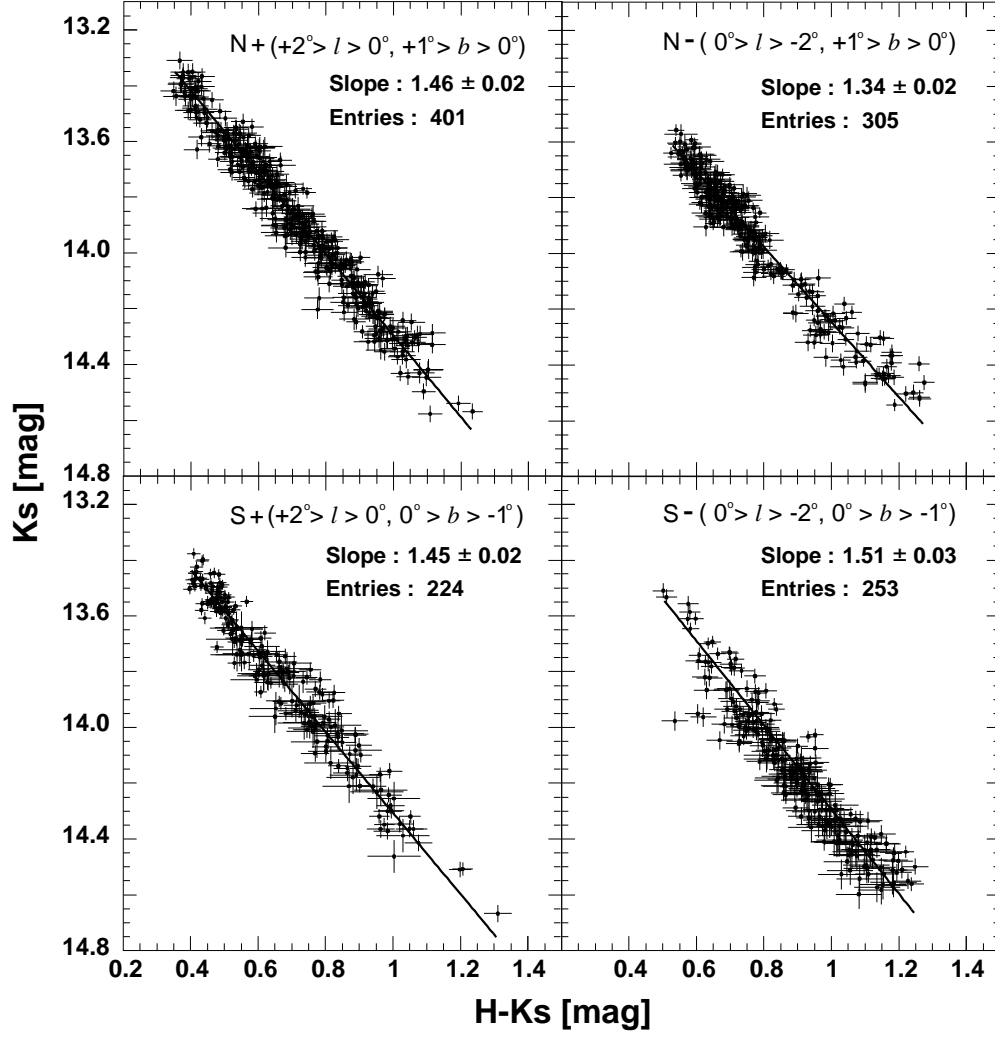


Fig. 5.— Variation of  $A_{K_S}/E_{H-K_S}$ . The solid lines are the least squares fits to the data.

## 5. Discussion

### 5.1. Possible Errors in $R$

An advantage of the RC method is the large number of RC stars, which makes their mean magnitude determination straightforward and precise. RC stars are also numerous in the solar neighborhood. Alves (2000) derived the average  $K$  band luminosity of 238 *Hipparcos* RC stars,  $M_K = -1.61 \pm 0.01$ , and their precise calibration is possible.

Population effects on the intrinsic magnitude and color of RC stars are the main error sources of the method. It is known that their brightness depends on their metallicity; however, the dependence is very weak ( $\lesssim 0.05$  mag / [M/H]; Salaris & Girardi 2002). To change the slope that we obtain, the metallicity distribution of RC stars in the bulge would have to be highly correlated with the extinction. Moreover, no metallicity gradient has been found in  $|l| \lesssim 4^\circ$  (Frogel et al. 1999; Ramírez et al. 2000).

Another error source is the variation of distance to RC stars, changing their mean magnitude by  $\sim 0.05$  mag along the Galactic longitude in the current observation range (Nishiyama et al. 2005). This difference can change the slope  $A_{K_S}/E_{H-K_S}$  of 1.44 [ $\Delta K_S/\Delta(H-K_S) = 1.37/0.95$ , see the  $K_S$  vs.  $H-K_S$  CMD in Fig. 3] to 1.49 ( $=1.42/0.95$ ). The change is only 0.05, even if the distance is completely correlated with the extinction, which is very unlikely. Therefore we conclude that the variation of the metallicity and distance does not affect our results.

The change in the extinction law, as shown in Fig. 5, suggests that within a single field, there may also be similar variations that would produce a selection bias in the results. To estimate the size of such bias, we divide the data points plotted in the  $K_S$  versus  $H-K_S$  CMD into two groups: those having a counterpart in the  $K_S$  versus  $J-K_S$  CMD (bluer sources) and those without one (redder sources). The former has a color distribution  $0.4 \lesssim H-K_S \lesssim 0.7$  and a slope  $A_{K_S}/E_{H-K_S} = 1.46$ , and the latter has  $0.5 \lesssim H-K_S \lesssim 1.2$  and  $A_{K_S}/E_{H-K_S} = 1.43$ . This means that the selection bias due to the extinction, which probably reflects the distribution of sources along the lines of sight, produces an uncertainty of only a few per cent in our results. This small uncertainty is also confirmed by the consistency of  $E_{J-H}/E_{H-K_S} \approx 1.7$  derived by the distribution of RC stars in the color-color ( $E_{J-H}$  vs.  $E_{H-K_S}$ ) diagram (Fig. 4) and derived by the product of  $A_H/E_{J-H}$  and  $A_H/E_{H-K_S}$ . Note that the sources whose  $J$  magnitudes have been determined form a small sub-group.

The IRSF/SIRIUS system is similar to the MKO system (Tokunaga et al. 2002), and the effective wavelengths following equation (A3) of Tokunaga & Vacca (2005) are calculated for a typical bulge RC star when it suffers extinction of  $A_{K_S} \sim 0.4-1.6$  (the range of extinction in

Fig. 3). We have employed a model of Kurucz (1993) with the parameters of  $T_{\text{eff}} = 4750\text{K}$ ,  $[\text{M}/\text{H}] = -0.1$  dex, and  $\log g = 2.0$ , and a power-law extinction curve (see §5.3). The effective wavelengths change by  $\sim 0.01\mu\text{m}$  to the longer wavelengths as the star suffers more extinction, and the mean effective wavelengths of the  $J$ ,  $H$ , and  $K_s$  filters are 1.25, 1.64, and  $2.14\mu\text{m}$ , respectively. The changes are small, and these wavelengths are not very sensitive to the source spectral energy distribution, and we thus conclude that the effective wavelengths can be uniquely defined for our study.

## 5.2. Comparison with Previous CD Method Studies

Previous results in the literature are listed for comparison in Table 1. Our results show a clear difference from those obtained in previous work. The ratios of total to selective extinction determined in this study are smaller, which corresponds to faster decrease in the absolute extinction  $A_\lambda$  when the wavelength increases. Therefore, the resulting power-law index  $\alpha$  is larger in this study.

The theoretical curve No. 15 of van de Hulst (1946, hereafter vdH) based on the Mie scattering theory has been used to estimate the wavelength dependence and is still favored by several authors (e.g., Glass 1999; Jiang et al. 2003). Our results are the closest in agreement to vdH.

Rieke & Lebofsky (1985, hereafter R&L) determined the near-infrared extinction law by applying the CD method to their observations of five supergiants near the GC and  $\alpha$  Sco. Their results have quite often been referred to as the standard extinction law, especially toward the GC, so let us examine them. Their observations were made in the  $K$  band, not  $K_s$ , but we can use results of Cardelli et al. (1989, hereafter CCM89) derived by the analytic formula of the average extinction law for  $0.9\mu\text{m} \leq \lambda \leq 3.3\mu\text{m}$  by fitting the data of R&L with a power law. Since the CD method requires the ratio of total to selective extinction, R&L set  $E_{V-K}/E_{B-V} = 2.744$  and assumed  $R_V = A_V/E_{B-V} = 3.09$  for the GC sources to evaluate  $A_\lambda/E_{B-V}$  and  $A_\lambda/A_V$ . While their assumption of  $R_V$  is reasonable, a small change in  $R_V$  results in a large difference in  $A_\lambda/E_{B-V}$  at near-infrared wavelengths (see eq. [2]). If  $R_V$  toward the GC is  $R_V = 3.00$ , which is smaller by only 0.09 than that in R&L, we obtain the ratio  $A_J/A_V : A_H/A_V : A_K/A_V = 0.260 : 0.150 : 0.085$  with their  $E_{\lambda-V}/E_{B-V}$ . These ratios are in fact similar to the ratios shown by vdH,  $A_J/A_V : A_H/A_V : A_K/A_V = 0.245 : 0.142 : 0.081$ . Although the lower limit of  $R_V$  in R&L was determined by the extinction at  $L$ ,  $M$ ,  $8\mu\text{m}$ , and  $13\mu\text{m}$ , the observations at these wavelengths have relatively large uncertainties. We also note that the extinction law that they derived in the wavelength range  $L$ ,  $M$ , and  $8\mu\text{m}$  is inconsistent with those obtained toward the GC, in

Table 1: The wavelength dependence of the interstellar extinction.

	IRSF	vdH <sup>a</sup>	R&L <sup>b</sup>	CCM89 <sup>c</sup>	He <sup>d</sup>	Indebetouw <sup>d</sup>
$A_{K_S}/E_{H-K_S}$	$1.44 \pm 0.01$	1.58	–	1.83	–	1.82
$A_K/E_{H-K}$	–	1.33	1.78	1.63	1.68	–
$A_{K_S}/E_{J-K_S}$	$0.494 \pm 0.006$	0.55	–	0.73	–	0.67
$A_K/E_{J-K}$	–	0.49	0.66	0.68	0.63	–
$A_H/E_{J-H}$	$1.42 \pm 0.02$	1.38	1.64	1.88	1.61	1.63
$A_H/A_J$	$0.573 \pm 0.009$	0.58	0.62	0.65	0.62	0.62
$A_{K_S}/A_J$	$0.331 \pm 0.004$	0.36	–	0.42	–	0.40
$A_K/A_J$	–	0.33	0.40	0.40	0.39	–
$\alpha$	$1.99 \pm 0.02$	1.80	1.54	1.61	1.73	1.65
References		1	2	3	4	5

<sup>a</sup>Calculated from the theoretical curve

<sup>b</sup>Observations toward the GC

<sup>c</sup>Analytic formula derived from R&L results

<sup>d</sup>Averaged ratios derived from observations toward many lines of sight

References. — (1) van de Hulst (1946); (2) Rieke & Lebofsky (1985); (3) Cardelli et al. (1989); (4) He et al. (1995); (5) Indebetouw et al. (2005)

particular by spectroscopy with the *Infrared Space Observatory (ISO)* for  $\lambda \geq 2.4\mu\text{m}$  (Lutz et al. 1996; Lutz 1999, see §5.3). Therefore, although the inconsistency might be the result of spatial variation of the extinction law examined in the previous section, it is also quite possible that the inconsistency was caused by the uncertainty of  $R_V$  in the CD method.

Indebetouw et al. (2005) derived  $A_\lambda/A_{K_S}$  by the CD method, using data of the *Spitzer Space Telescope (SST)* and Two Micron All Sky Survey (2MASS) along two lines of sight ( $l = 42^\circ$  and  $284^\circ$ ) in the Galactic plane. They observed RC stars and determined  $A_\lambda/A_{K_S}$  for  $1.25\mu\text{m} \leq \lambda \leq 8.0\mu\text{m}$ . They measured color excess ratios  $E_{\lambda-K_S}/E_{J-K_S}$  by fitting the locus of RC stars in color-color diagrams. To derive  $A_\lambda/A_{K_S}$  from  $E_{\lambda-K_S}/E_{J-K_S}$ , they first determined  $A_J/A_{K_S}$  by fitting the RC locus in a CMD. Since the fields of  $l = 42^\circ$  and  $284^\circ$  are dominated by the disk stars, which are located at different distances from us, they assumed that the extinction per unit distance is constant to fit the RC locus. Their results are also different from ours. We notice, however, that the intercept of  $E_{\lambda-K_S}/E_{J-K}$  at  $\lambda^{-1} = 0$  in

their Fig. 5 seems to be larger (less negative) than their result obtained by fitting the RC locus in CMD  $-A_{K_S}/E_{J-K} = -0.67$ , but rather close to our result  $-0.494$ . Although the data of the *SST* have the potential to establish the extinction law for  $3.55\mu\text{m} \leq \lambda \leq 8.0\mu\text{m}$ , the uncertainty of  $A_J/A_{K_S}$  affects  $A_\lambda/A_{K_S}$  at these wavelengths, and thus the determination of  $A_J/A_{K_S}$  should be approached cautiously.

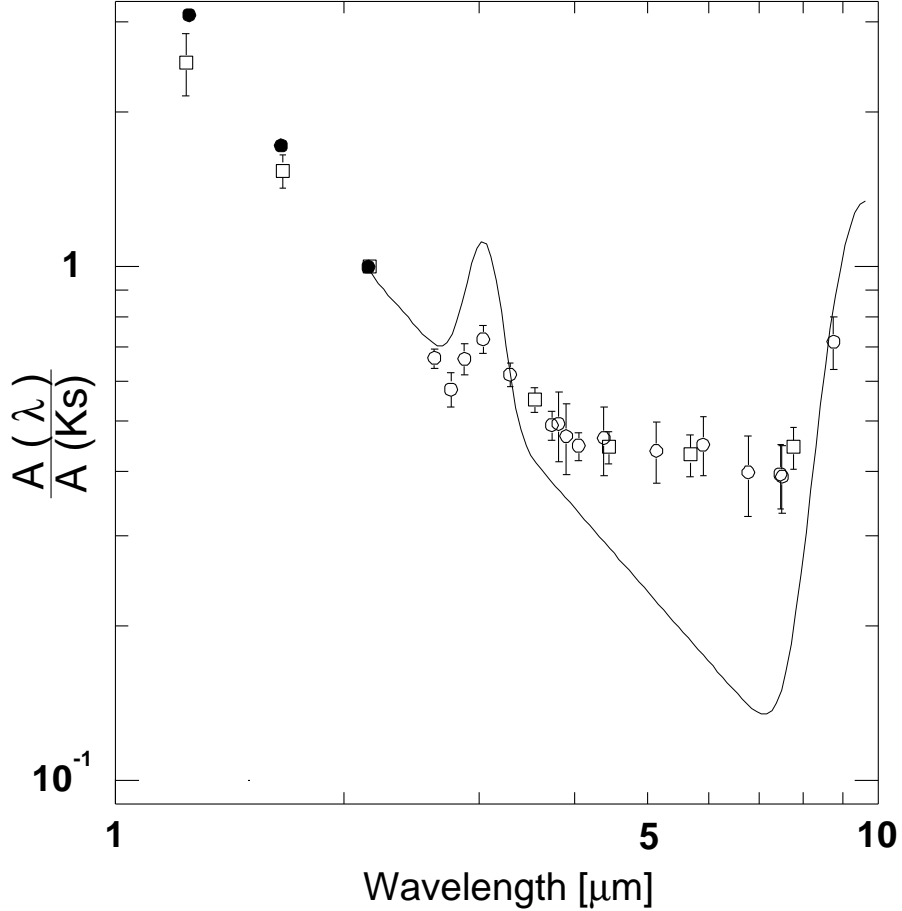


Fig. 6.— Comparison of extinction ratio ( $A_\lambda/A_{K_S}$ ) toward the Galactic center (this work [*filled circles*] and Lutz et al. 1996 [*open circles*]), and other regions. The solid line is found from the relative intensities of the  $\text{H}_2$  lines toward the emission peak of Orion OMC-1 (eq. 2 of Rosenthal et al. 2000). The average of three fields in the Galactic plane (Indebetouw et al. 2005) is also shown (*open squares*).

### 5.3. Power-Law Extinction in the Infrared

It is frequently remarked that the continuous extinction curve between  $\sim 0.9$  and  $\sim 5\mu\text{m}$  can be approximated by a power-law  $A_\lambda \propto \lambda^{-\alpha}$  (Draine 2003). However, the power-law fitting has been based on the CD method, and is not free from the offset errors of eq. [1]. In contrast, without any a priori assumptions about the extrapolation to the longer wavelengths, our new results are fitted very well by the function with  $\alpha = 1.99 \pm 0.02$  (see the three data points that are very well aligned in Fig. 6). Here we have used the mean effective wavelengths of the  $J$ ,  $H$ , and  $K_S$  filters determined in §5.1. This good fit presents, for the first time, direct evidence for the power-law approximation in the wavelength range of  $1.2\text{--}2.2\mu\text{m}$ .

This corroborates the method of determining the absolute extinction on the assumption of a power law in the near-infrared without resorting to the CD method. This wavelength range has no absorption features so far identified in either the diffuse or molecular interstellar medium. Therefore, we proceed with the power-law approximation, which is expressed by a straight line in a logarithmic graph like Fig. 6, and compare the index  $\alpha$  in the measurements in the literature. This also mitigates the difference between various photometric systems used in the near-infrared, whose problems have been pointed out by Kenyon et al. (1998).

He et al. (1995) made photometry of 154 obscured OB stars in the southern Milky Way. They basically employed the CD method but derived the absolute extinction also, on the assumption that the interstellar extinction follows a power-law. Although their observation shows considerable scatter (as suggested by their Fig. 9; also see their Fig. 10), the average extinction is clearly different from our results (Table 1).

Also on the assumption of power-law extinction, Moore et al. (2005) determined the power-law index  $\alpha$  toward a set of nine ultracompact H II regions and two planetary nebulae with  $0.27 \lesssim \tau(\text{Br}\gamma) \lesssim 4.7$ . Their observations of hydrogen recombination lines at  $1.0\mu\text{m} \lesssim \lambda \lesssim 2.2\mu\text{m}$  showed that the power-law index  $\alpha$  varies from 1.1 to 2.0 and a clear tendency that  $\alpha$  is smaller for higher extinction regions. They suggest that the flatter near-infrared extinction laws might be the result of grain growth in the regions of higher extinction. The steep extinction law determined toward the GC in this study, then, might mean that the interstellar medium in its line of sight is largely diffuse. A steep index of 2 in the *polarization*, which is supposed to indicate the difference of two orthogonal extinctions, of GC objects is also reported by Nagata et al. (1994). Although it has been suggested that interstellar extinction remains relatively invariant ( e.g., CCM89 ) in the near-infrared region (  $\lambda \gtrsim 0.7\mu\text{m}$  ), these studies indicate clear variation in the extinction law.

At longer wavelengths, two sets of extinction determination from the emission line ratios using the Short Wavelength Spectrometer on board *ISO* have been reported toward the GC

(Lutz et al. 1996; Lutz 1999) and Orion (Rosenthal et al. 2000). Although these two studies have assumed the absolute extinction values at some wavelengths and therefore are vulnerable to offset errors, the extinction law toward the GC seems to be clearly different from that of Rosenthal et al. (2000), especially in the range  $2.5\mu\text{m} \lesssim \lambda \lesssim 8\mu\text{m}$  (Fig. 6). In the GC Lutz (1999) points out that the extinction becomes flatter at  $\lambda \gtrsim 2.5\mu\text{m}$  and lacks the pronounced minimum near  $7\mu\text{m}$  expected for the standard grain models; this flatter slope or addition of another extinction component is also observed in the polarimetry of the GC objects at  $2.8 - 4.2\mu\text{m}$  (Nagata et al. 1994). Our extinction law, which has steeper exponents in the wavelength range of  $1.2 - 2.2\mu\text{m}$ , and other studies discussed above lead to the conclusion that the extinction law varies from one line of sight to another even in the near-infrared wavelength range.

## 6. Conclusion

The ratios of total to selective extinction  $A_{K_S}/E_{H-K_S} = 1.44 \pm 0.01$ ,  $A_{K_S}/E_{J-K_S} = 0.494 \pm 0.006$ , and  $A_H/E_{J-H} = 1.42 \pm 0.02$  have been directly obtained toward the Galactic center from the observation of bulge red clump stars. Then the ratio of absolute extinction  $A_J : A_H : A_{K_S} = 1 : 0.573 \pm 0.009 : 0.331 \pm 0.004$  is obtained, and the power law approximation  $A_\lambda \propto \lambda^{-1.99}$  is shown to be good enough in the wavelength range of  $1.2 - 2.2\mu\text{m}$ . These values are clearly different from those obtained in previous studies toward the Galactic center and other lines of sight. The previous extrapolation procedures might have caused the difference, although the observed color excesses in the literature can be consistent with the current results. Furthermore, small variations in the ratio of total to selective extinction do exist among the sub-regions in the current study. This indicates that, contrary to the widely accepted ideas, the extinction law is not “universal” even in the infrared, and therefore one should be extremely cautious about applying reddening corrections.

We would like to thank the IRSF/SIRIUS team and J. F. Koerwer for their helpful comments. We also thank the staff at SAAO for their support during our observations. The IRSF/SIRIUS project was initiated and supported by Nagoya University, the National Astronomical Observatory of Japan and the University of Tokyo in collaboration with the South African Astronomical Observatory under Grants-in-Aid for Scientific Research No.10147207, No.10147214, No.13573001, and No.15340061 of the Ministry of Education, Culture, Sports, Science and Technology (MEXT) of Japan. This work was also supported in part by the Grants-in-Aid for the 21st Century COE “The Origin of the Universe and Matter: Physical Elucidation of the Cosmic History” and “Center for Diversity and Universality in Physics” from the MEXT of Japan.



## REFERENCES

- Alves, D. R., 2000, *ApJ*, 539, 732
- Cardelli, J. A., Clayton, G. C., & Mathis, J. S., 1989, *ApJ*, 345, 245 (CCM89)
- Draine, B. T., 2003, *ARA&A*, 41, 241
- Frogel, J. A., Tiede, G. P., & Kuchinski, L. E., 1999, *AJ*, 117, 2296
- Glass, I. S., 1999, *Handbook of Infrared Astronomy* (Cambridge Univ. Press)
- He, L., Whittet, D. C. B., Kilkenney, D., & Spencer Jones, J. H., 1995 *ApJS*, 101, 335
- Indebetouw, R., et al., 2005, *ApJ*, 619, 931
- Jiang, B. W., Omont, A., Ganesh, S., Simon, G., & Schuller, F., 2003, *A&A*, 400, 903
- Kenyon, S. J., Lada, E. A., & Barsony, M., 1998, *AJ*, 115, 252
- Krelowski, J., & Papaj, J., 1993, *PASP*, 105, 1209
- Kurucz, R. L., 1993, in *IAU Colloq. 138, Peculiar versus Normal Phenomena in A-Type and Related Stars*, ed. M. M. Dworetsky, F. Castelli, & R. Faraggiana (ASP Conf. Ser. 44; San Francisco: ASP), 87
- Lutz, D., et al., 1996, *A&A*, 315, L269
- Lutz, D., 1999, in *The Universe as Seen by ISO*, ed. P. Cox & M. F. Kessler (ESA SP-427; Noordwijk: ESA), 623
- Mihalas, D., & Binney, J., 1981, *Galactic Astronomy* (2nd ed.; San Francisco: Freeman)
- Moore, T. J. T., Lumsden, S. L., Ridge, N. A., & Puxley, P. J., 2005, *MNRAS*, 359, 589
- Nagashima, C., et al., 1999, in *Star Formation 1999*, ed. T. Nakamoto (Nobeyama : Nobeyama Radio Obs.), 397
- Nagata, T., Kobayashi, N., & Sato, S., 1994, *ApJ*, 423, L113
- Nagayama, T., et al., 2003, *Proc. SPIE*, 4841, 459
- Nishiyama, S., et al., 2005, *ApJ*, 621, L105
- Persson, S. M., Murphy, D. C., Krzeminski, W., Roth, M., & Rieke, M. J., 1998, *AJ*, 116, 2475

- Rieke, G. H., & Lebofsky, M. J., 1985, *ApJ*, 288, 618 (R&L)
- Ramírez, S. V., Stephens, A. W., Frogel, J. A., & DePoy, D. L., 2000, *AJ*, 120, 833
- Rosenthal, D., Bertoldi, F., & Drapatz, S., 2000, *A&A*, 356, 705
- Salaris, M., & Girardi, L., 2002, *MNRAS*, 337, 332
- Stetson, P. B., 1987, *PASP*, 99, 191
- Sumi, T., 2004, *MNRAS*, 349, 193
- Tokunaga, A. T., Simons, D. A., & Vacca, W. D., 2002, *PASP*, 114, 180
- Tokunaga, A. T., & Vacca, W. D., 2005, *PASP*, 117, 421
- Udalski, A., 2003, *ApJ*, 590, 284
- van de Hulst, H. C., 1946, *Rech. Astron. Obs. Utrecht*, 11, 1
- Woźniak, P. R., & Stanek, K. Z., 1996, *ApJ*, 464, 233